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THE EFFECT OF ENVIRONMENT ON THE FATIGUE STRENGTHS OF FOUR SELECTED ALLOYS

by T. R. Shives and J. A. Bennett

Prepared under Contract No. R-14 *by*
NATIONAL BUREAU OF STANDARDS
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SUMMARY

Rotating beam fatigue tests of unnotched specimens of AISI 4340 steel, free-cutting brass, titanium alloy Ti-4Al-4Mn, and magnesium alloy AZ61A showed that the fatigue strength was lower in a moist environment than in a dry one. A coating of dodecyl alcohol was found to have a beneficial effect on the fatigue strength of the steel and magnesium alloy specimens, but did not completely eliminate the effect of humidity. The effect of environment on crack propagation was investigated with notched specimens of the magnesium alloy. An interesting tarnishing effect was observed on the fatigue portion of magnesium fracture surfaces.

INTRODUCTION

More than 30 years ago Gough and Sopwith (1) found that the fatigue strengths of many structural metals were lower in a normal atmosphere than they were in vacuum. In recent years there has been a renewed interest in many aspects of atmospheric corrosion fatigue, and the National Bureau of Standards has been conducting investigations in this field under National Aeronautics and Space Administration sponsorship. An earlier paper (2) reviewed the pertinent information in the literature up to early 1961; the present paper is a report of further work on this project.

Broom and Nicholson (3) established that water vapor is the only constituent of the normal atmosphere that affects the fatigue behavior of age-hardened aluminum alloys. The situation is not so clear for other structural metals and there is a need for additional work to evaluate the effects of particular atmospheric constituents on the fatigue strengths of a variety of metals. Knowledge of the effects of surface reactions will help in understanding the mechanism of fatigue crack initiation, as it has in the case of aluminum alloys (4). Since it is relatively easy to control humidity, and water vapor is thought to have an important effect on the fatigue properties of many metals, the first group of experiments was planned to evaluate the effect of varying humidity. The materials selected included four of the most common classes of structural metals except aluminum alloys; these were omitted because they had been studied previously (4).

Another purpose of this investigation was to determine if the beneficial effect of certain polar organic liquids (5) is due only to the ability of the liquid film to protect the surface of the metal. Accordingly some of the materials were tested with a film of dodecyl alcohol as well as in the clean condition. Previous work had shown that this liquid was convenient to use and resulted in nearly the same improvement in fatigue behavior as the most effective compounds investigated (5).

SYMBOLS

The symbols used in this paper are defined below.

S_A Stress amplitude

N_F Cycles to failure

N_p Cycles for crack propagation

$\longrightarrow$ Runout - 20 x 10^6 cycles without failure.

MATERIALS AND TESTING PROCEDURES

The four materials selected for this investigation are listed in Table I.

TABLE I. MATERIALS

Material	Condition	Analysis (a)		Tensile Strength (b) psi	Tensile Strength (b) MN/m^2
1. AISI 4340 Steel	Ser. I. Q - 1475 F	C	0.40 %	156,000	1076
	T - 1100 F	Cr	0.77		
	33 R_C	Mn	0.67		
	Ser. II. Q - 1475 F	Mo	0.20		
	T - 1150 F	Ni	1.74		
	29 R_C	Si	0.27		
2. Titanium Alloy Ti-4Al-4Mn	Hot rolled, annealed	Al	4.2 %	149,000	1027
		C	<0.1		
		Mn	3.8		
		H_2	0.006		
		N_2	0.02		
3. Brass, Federal Specification Composition 22	One-half hard 78 R_B	Cu	60-63 %	62,100	428
		Fe	0.15 max.		
		Pb	2.5-3.7		
		Zn	33-36		
		Others	0.50		
4. Magnesium Alloy AZ61A	Extruded	Al	5.9 %	47,800	330
		Cu	<0.01		
		Fe	0.005		
		Mn	0.38		
		Ni	0.001		
		Si	<0.05		
		Zn	0.82		

(a) Analysis by producer for materials 1, 2, and 4; specification limits only given for brass, no analysis made.

(b) Data for materials 1, 3, and 4 obtained by authors; data for Ti-4Al-4Mn obtained from G. W. Geil of National Bureau of Standards for same batch of material.

The fatigue specimens were of the R. R. Moore type (fig. 1). All were smooth except for one series of notched magnesium alloy specimens.

The steel specimens were rough machined and then heat treated before grinding. All other specimens were finish machined with a lathe cutting tool. Smooth specimens were then polished longitudinally on abrasive paper, the final polish being obtained with No. 400 paper. Series II steel specimens and some of the magnesium specimens were wet polished. All others were dry polished. Before testing, all specimens were washed successively in three containers of high purity benzene.

The diameter of the reduced section was nominally 0.240 in. (0.608 cm.) for the brass, steel, and some of the smooth magnesium specimens, 0.200 in. (0.508 cm.) for the titanium specimens, and 0.300 in. (0.762 cm.) for the rest of the smooth magnesium specimens. The notched specimens had a diameter of nominally 0.300 in. (0.762 cm.) at the notch root.

Fatigue tests were conducted on R. R. Moore rotating beam machines which apply a uniform bending moment with a constant stress amplitude. Machine speeds were maintained at about 9000 rpm and all tests were conducted at room temperature. In order to control the humidity, the tests were conducted in closed chambers (6) which consisted essentially of a thin plastic sleeve between the end plates of the bearing boxes. For high humidity tests, the relative humidity was maintained at 85 percent or higher by introducing into the chamber laboratory supply air that had been bubbled through water. For low humidity tests (relative humidity less than 3%), laboratory supply air was passed through drying towers containing silica gel.

In most of the tests on specimens coated with dodecyl alcohol, the alcohol was applied to the reduced section of the specimen with a cotton swab before the test was started. In a few tests of the notched specimens, dodecyl alcohol was dripped onto the specimens during testing. No significant difference in results was noted due to the method of application.

RESULTS OF FATIGUE TESTS

AISI 4340 Steel

Fatigue tests were made on both clean and dodecyl alcohol coated 4340 specimens. There were two groups of specimens, series I having a hardness of 33 R_C and series II having a hardness of 29 R_C. The results of these tests are shown in Table II. Judging by the results of series I tests (figs. 2 and 3), water vapor appears to have only a small effect on the fatigue limit of both clean and coated specimens. There also appears to be a significant improvement in fatigue life for coated specimens in both dry and moist environments. Unfortunately due to a shortage of specimens and time, the fatigue limit for low humidity conditions for series I was not established (fig. 3).

TABLE II. FATIGUE TESTS RESULTS FOR AISI 4340 STEEL

S_A		N_F							
		Series I				Series II			
		Clean		Coated with Dodecyl Alcohol		Clean		Coated with Dodecyl Alcohol	
Ksi	MN/m^2	Low Humidity	High Humidity	Low Humidity	High Humidity	Low Humidity	High Humidity	Low Humidity	High Humidity
86	593		→						
87	600		→			153×10^3			299×10^3
			4951×10^3			113			276
						85			205
88	607	→	→						
		→	233						
89	614	→		→	748×10^3				
		→		→					
		→							
90	621	503×10^3	571	1323×10^3	723		92×10^3	232×10^3	174
		394					86	132	
		367	259	1291	560		72	118	
		214							
91	627		388						
92	634			1207	293				
				477	169				
95	655	560	402						
		314	256			68	80	113	82
		222	178			64	71	102	75
		195	116			61	64	70	71
		119	107						
100	689					47	51	61	53
						40	41	59	51
						32	30	42	28

In figure 4 no distinction is made between low and high humidity tests, the S-N curves being plotted to show the effect of the dodecyl alcohol coating only. In all cases, the coating was beneficial, but the improvement was not as great as that found in the earlier experiments with the same alloy reported in reference 5.

Titanium Ti-4Al-4Mn Alloy

There was considerable dispersion in the results for the titanium alloy specimens, as shown in Table III. In order to be able to observe the trends more easily, the values plotted in figure 5 were obtained by averaging the results at two stress amplitudes one ksi (6.9 MN/m^2) apart. It is clear that high humidity has a deleterious effect on the fatigue limit, the difference at 50% runouts being equivalent to about 5% in stress amplitude. No attempt was made to obtain data in the finite life part of the S-N curve.

There was more difficulty with fretting in the collets with these specimens than with the other materials tested. The first titanium specimens tested had a diameter of 0.24 in. (0.608 cm.) in the reduced section. During testing, fatigue caused by fretting between the specimen shank and the collet used to hold the specimen in the spindle produced premature failure in the shank in several specimens. The diameter of the test section was reduced to 0.20 in. (0.508 cm.) in later specimens. Failure in the shank due to fretting was not entirely eliminated, but it was greatly lessened. All of the data presented in Table III and figure 5 were obtained from 0.20 in. (0.508 cm.) diameter specimens. The titanium alloy exhibited a true fatigue limit behavior at a stress amplitude of approximately 100 ksi (690 MN/m^2). This is remarkably high in comparison with most steels and aluminum alloys on the basis of either fatigue strength: density ratio or fatigue strength: tensile strength ratio, the latter being nearly 2/3. Panseri and Mori (7) found an almost equally high fatigue limit: tensile strength ratio for a weaker Ti-6Al-4V alloy.

Composition 22 Brass

The results for clean brass specimens tested in both low and high relative humidity are shown in Table IV and in figure 6. The fatigue strength in the high humidity environment was about 3% lower than that in a dry atmosphere throughout the range investigated.

Magnesium AZ61A alloy

Smooth specimens of AZ61A magnesium alloy were first made with a diameter of 0.30 in. (0.762 cm.) in the reduced section. After several specimens failed in the shank, the specimen diameter was reduced to 0.24 in. (0.608 cm.), which almost eliminated the difficulty.

TABLE III. FATIGUE TEST RESULTS FOR TITANIUM TI-4AL-4MN

S_A		N_F	
Ksi	MN/m^2	Low Humidity	High Humidity
92	634		→
95	655	→	84×10^3 → →
98	676	→ → → →	38×10^3 112 →
99	683	→ → →	51×10^3 →
100	689	78×10^3 78 145 161 →	41×10^3 55 638 →
101	696	→ → →	33×10^3 49 71
102	703	100×10^3 → →	34×10^3 50 64 205
103	710	56×10^3 85 3953 →	
105	724	72×10^3 115 139 →	
107	738	59×10^3 81 187	

TABLE IV. FATIGUE TEST RESULTS FOR FREE-CUTTING BRASS

S_A		Low Humidity		High Humidity	
Ksi	MN/m^2	No. of Specimens	N_F*	No. of Specimens	N_F*
30	207	3	4005×10^3	3	2712×10^3
31	214	2	2473	1	1921
32	221	2	2809	1	1889
34	234	3	1350	3	956
36	248	1	784	1	692
38	262	3	627	3	529

* Antilog log mean values

The results for the smooth magnesium alloy specimens are shown in Table V, and the S-N curves in figure 7. There was a good deal of dispersion in the data, but the effect of moisture on the fatigue behavior was pronounced. The deleterious effect of high humidity was greater at high stress levels than at the low end of the range investigated. Coating with dodecyl alcohol had a beneficial effect in the moist environment and to a lesser extent in the dry atmosphere. The difference in fatigue strength between the best (low humidity, coated) condition and the poorest (high humidity, clean) ranged from 13% at $N_F = 350 \times 10^3$ to only 3% at $N_F = 2000 \times 10^3$. In terms of fatigue life this is a smaller improvement than that reported in reference 5 for the much weaker cast material.

No consistent difference could be noted between the results with specimens that had been polished wet and those that had been polished dry.

A series of tests was conducted in order to determine the effect of humidity on crack propagation, using notched specimens of magnesium AZ61A. All tests were run at $S_A = 10$ Ksi ($69\ MN/m^2$). Preliminary tests were conducted to determine the number of cycles required to form a small crack. Specimens were sectioned after various numbers of cycles and examined microscopically, and it was found that a crack was usually present in clean specimens after 105×10^3 cycles in a low humidity atmosphere. On the basis of these results, all specimens were run clean under low humidity conditions for 105×10^3 cycles, then they were divided into four groups, each group being run to failure under one of the following conditions:

a) Clean, low relative humidity

b) Clean, high relative humidity

c) Coated with dodecyl alcohol, low relative humidity

d) Coated with dodecyl alcohol, high relative humidity

The results of these tests are shown in Table VI. It is clear that both humidity and the polar liquid had a significant effect, and the two effects seem to be nearly independent. The high humidity reduced the average crack propagation life by 64% from the life under condition "a" while the presence of the liquid film raised it by 35%.

TABLE V. FATIGUE TEST RESULTS FROM SMOOTH MAGNESIUM AZ61A

S_A		Low Humidity			
		Clean		Coated with Dodecyl Alcohol	
Ksi	MN/m^2	No. of Specimens	N_F*	No. of Specimens	N_F*
22	152	7	6082×10^3	3	5369×10^3
23.5	162	7	712		
25	172	17	375	9	450
27	186	8	311	5	344

S_A		High Humidity			
		Clean		Coated with Dodecyl Alcohol	
Ksi	MN/m^2	No. of Specimens	N_F*	No. of Specimens	N_F*
22	152	11	1922×10^3	4	3176×10^3
23.5	162	4	8245		
25	172	13	158	9	240
27	186	10	89	5	152

* Antilog log mean values

TABLE VI. FATIGUE TEST RESULTS FOR NOTCHED MAGNESIUM AZ61A
(S_A = 10 KSI, 69 MN/m^2)

(All specimens were stressed for 105,000 cycles under condition (a) to initiate a crack. N_p does not include these cycles.)

	Condition	No. of Specimens	N_p *
a	Low relative humidity, clean	7	521×10^3
b	High relative humidity, clean	3	201
c	Low relative humidity, coated with dodecyl alcohol	3	735
d	High relative humidity, coated with dodecyl alcohol	4	243

* Antilog log mean values

TARNISHING OF FRACTURE SURFACES

An interesting type of film formation was noted on fractures of the magnesium alloy specimens. When first broken the surfaces were bright, but several months after testing some of the surfaces had become discolored like that at the left in figure 8. Upon examining all of the fractured magnesium specimens, it was found that only those that had been tested in high humidity had tarnished in this way. The discoloration could be observed only on specimens that had been stored in closed containers, because otherwise the entire specimen acquired a grey coating. The tarnish film, which varied in color from greenish tan to dark grey, was exactly the same on both sides of each fracture (fig. 9) and was limited to that part of the surface which had failed in fatigue. By running more specimens and periodically looking at the fractures, it was found that the tarnish became noticeable within two to three weeks after fracture. Efforts to determine the nature of these films have thus far been unsuccessful.

DISCUSSION

All of the materials tested showed higher fatigue strengths in a dry atmosphere than in a moist one. However, the effect was relatively small except for the magnesium alloy. The results of the present experiments indicate that the decreases in fatigue strength for the steel, brass and titanium alloy were less than 5%, whereas Bennett (4), for example, has reported a decrease of 14% for an aluminum alloy over approximately the same range of humidity. A part of this difference may be due to the higher speed of the present tests, as it was shown in earlier work on this project (6) that the influence of high humidity is more pronounced at 3000 cpm than at 9000 cpm. The tests reported in reference 4 were run at only 1800 cpm.

Despite the possible mitigating effect of the high testing speed, it appears that the influence of humidity on fatigue strength of brass is much less than the effect of all atmospheric constituents, as indicated by the vacuum tests of Gough and Sopwith (1). They reported an improvement of 26% in the fatigue limit of annealed brass when tested in vacuum as compared with tests in air. Thus it is probable that constituents other than water vapor have an influence on the fatigue behavior of brass.

There are few data in the literature with which to compare the results on the 4340 steel. The vacuum tests of Gough and Sopwith indicated that the atmosphere reduced the fatigue strength of carbon steels only about 5%, but the work of Wadsworth (8) on iron suggests that the vacuum used by the earlier investigators was not high enough to give the maximum effect. Mantel, et. al. (9) tested hardened 52100 steel in argon and found a large detrimental effect on fatigue properties due to moisture. Additional work is needed to determine definitely if other atmospheric constituents affect the fatigue properties of heat-treated steel.

The present results are the only data on the atmospheric corrosion fatigue of titanium alloy that have come to our attention. In view of the marked reactivity of clean titanium surfaces, it seems quite possible that a larger effect of water vapor would be found if tests were run in very dry environments. These results, then, are primarily of value in showing that the fatigue behavior is not greatly influenced over the range of humidities to be expected in the normal atmosphere. One cannot conclude from them, however, that water vapor is unimportant in the fatigue behavior of titanium.

The effect of humidity on the magnesium alloy was the most marked of the materials investigated. This is probably due to the highly reactive nature of the metal combined with a more permeable oxide film than that of either aluminum or titanium. The results of the experiments with dodecyl alcohol on the specimens suggested that its effect was similar to that of reducing the humidity. Such an effect would be expected if the liquid reduced the rate at which moisture reached the metal surface, but it does not rule out the possibility that other gases also affect the fatigue behavior in this material. It is obvious that the film of liquid is not preventing all of the water vapor from reaching the surface, as the fatigue strength of coated specimens in high humidity was less than that of clean specimens in dry air.

The large effect of humidity on the rate of crack propagation in the notched magnesium alloy specimens suggests that much of the effect observed on smooth specimens may be accounted for by the crack propagation stage of the life. This is borne out by the fact that the influence of moisture is more pronounced at high stress levels where the crack propagation stage would be expected to occupy a larger part of the total life than at lower stresses.

The observation of tarnishing on the fracture surfaces of magnesium alloy specimens is novel in that it appears to depend critically on the method of propagation of the fracture. The film was formed only on these areas that had fractured by fatigue in high humidity. The phenomenon is of interest, therefore, not only because of its possible value in understanding the role of water vapor in fatigue, but also because it can provide a method for distinguishing the portions of a fracture due to fatigue crack propagation from those formed in the final rapid fracture.

CONCLUSIONS

Results of rotating beam fatigue tests in moist and dry atmospheres appear to justify the following conclusions:

1. The moist atmosphere had a deleterious effect on the fatigue strength of all the materials investigated (low alloy steel, brass, titanium alloy, magnesium alloy). Except for the magnesium alloy, the decrease in strength was less than 5%.

2. The fatigue limit of the titanium alloy was approximately two thirds of the tensile strength.

3. The effect of a polar organic liquid was investigated with the steel and the magnesium alloy. The presence of the liquid film increased the fatigue strength of both materials but did not completely protect the metal from the effects of water vapor.

4. Comparison of these results with those in the literature suggests that water vapor is not the only constituent of the atmosphere that affects the fatigue properties of brass.

5. There is evidence from the magnesium alloy tests that the influence of humidity is more pronounced during crack propagation than during the initiation stage.

6. A tarnish film which was observed to form on the fracture surfaces of magnesium alloy specimens appears to offer a means for identifying the portion of a fracture which was due to fatigue crack propagation.

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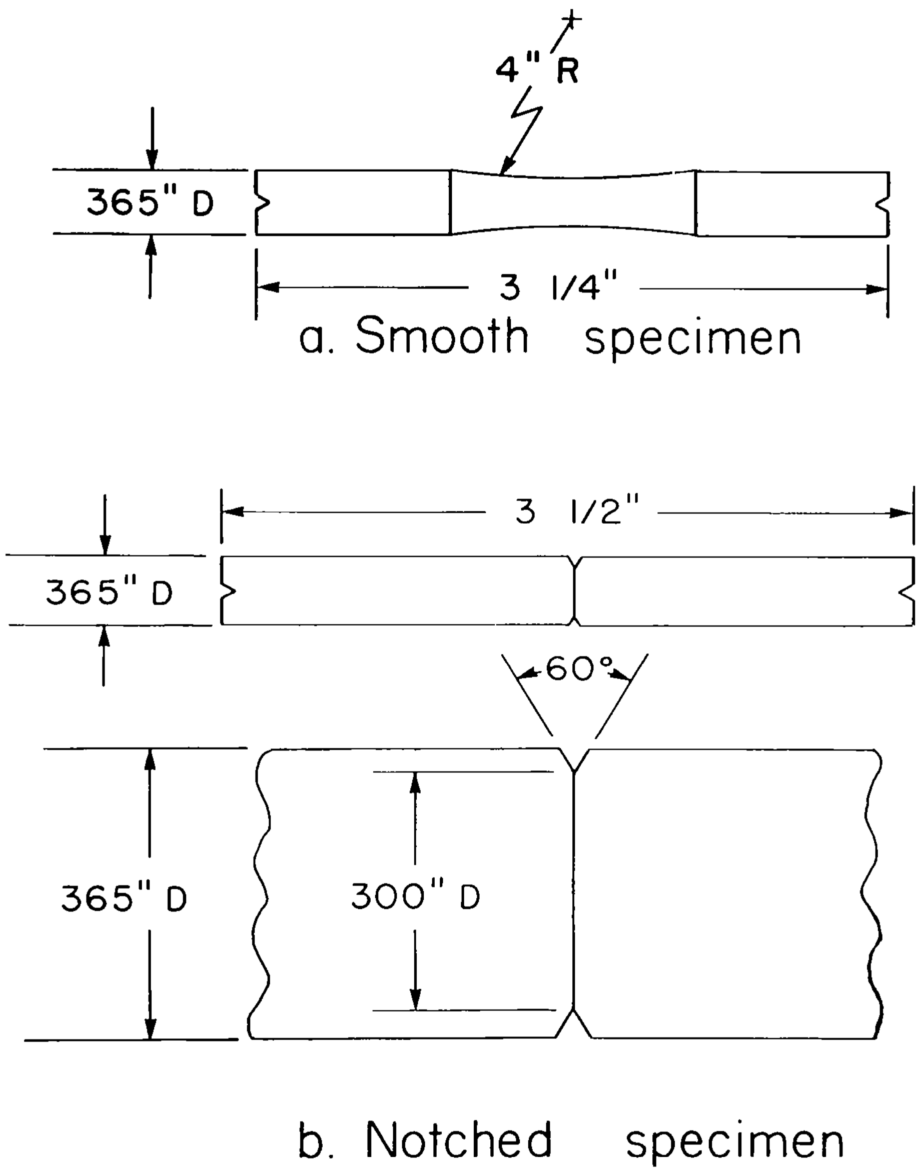

Fig. 1. Fatigue test specimens.

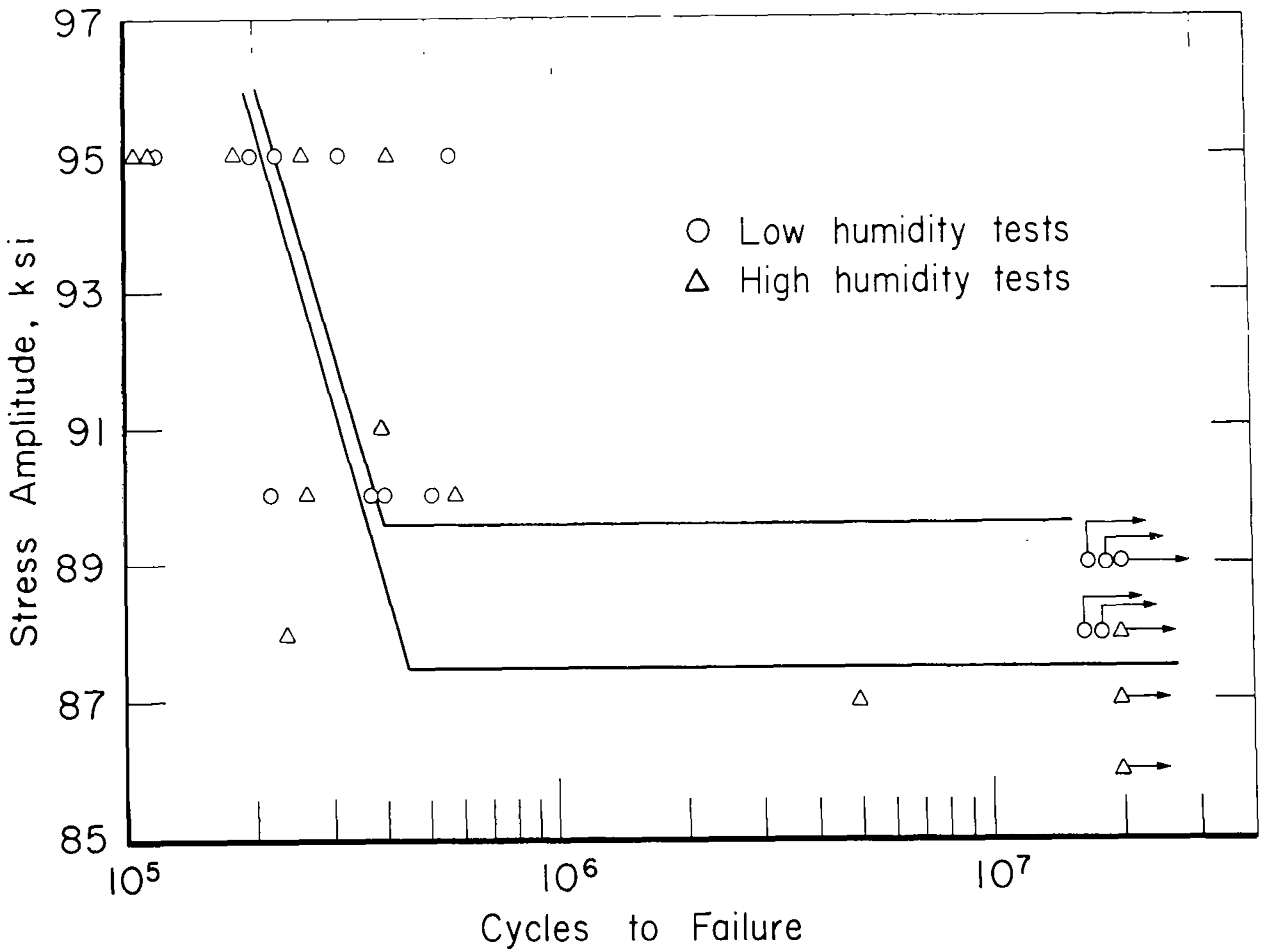

Fig. 2. Effect of humidity on fatigue strength of clean 4340 steel - series 1.

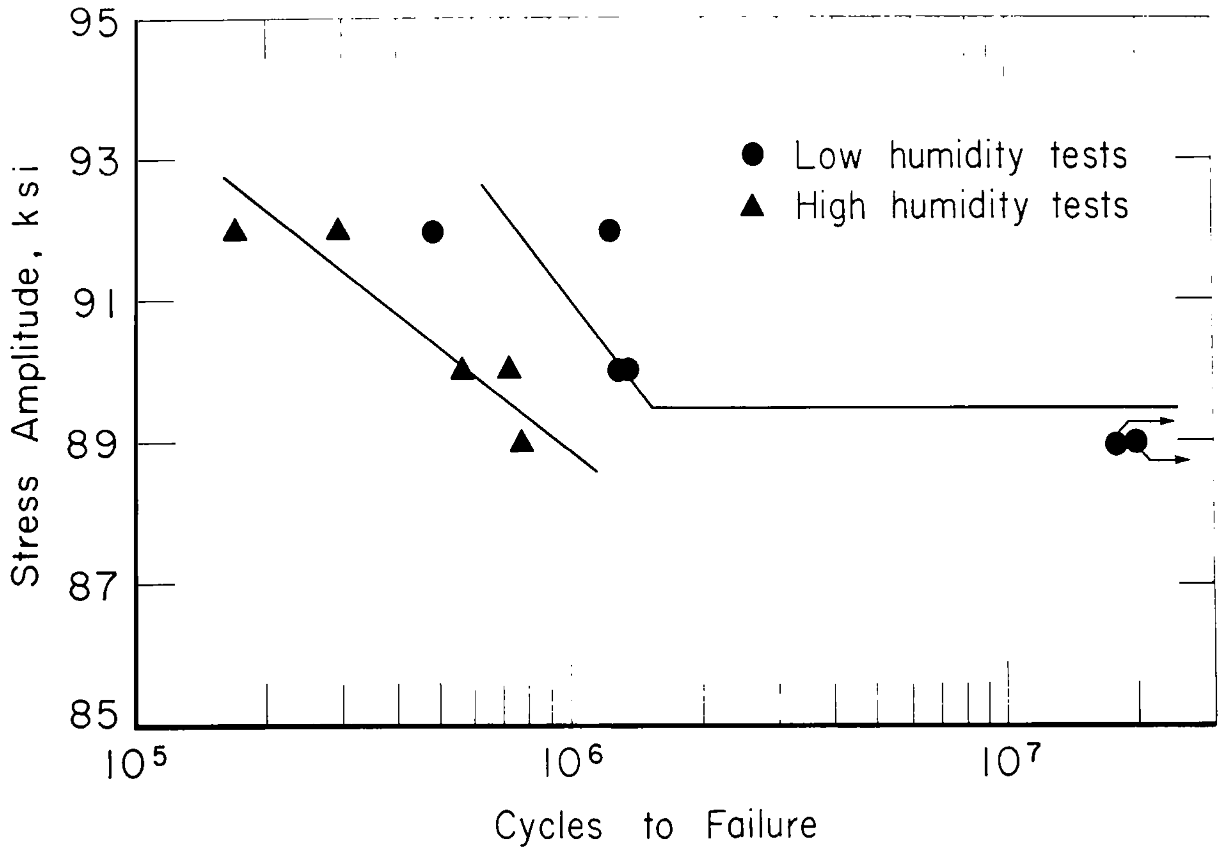

Fig. 3. Effect of humidity on fatigue strength of coated 4340 steel - series I.

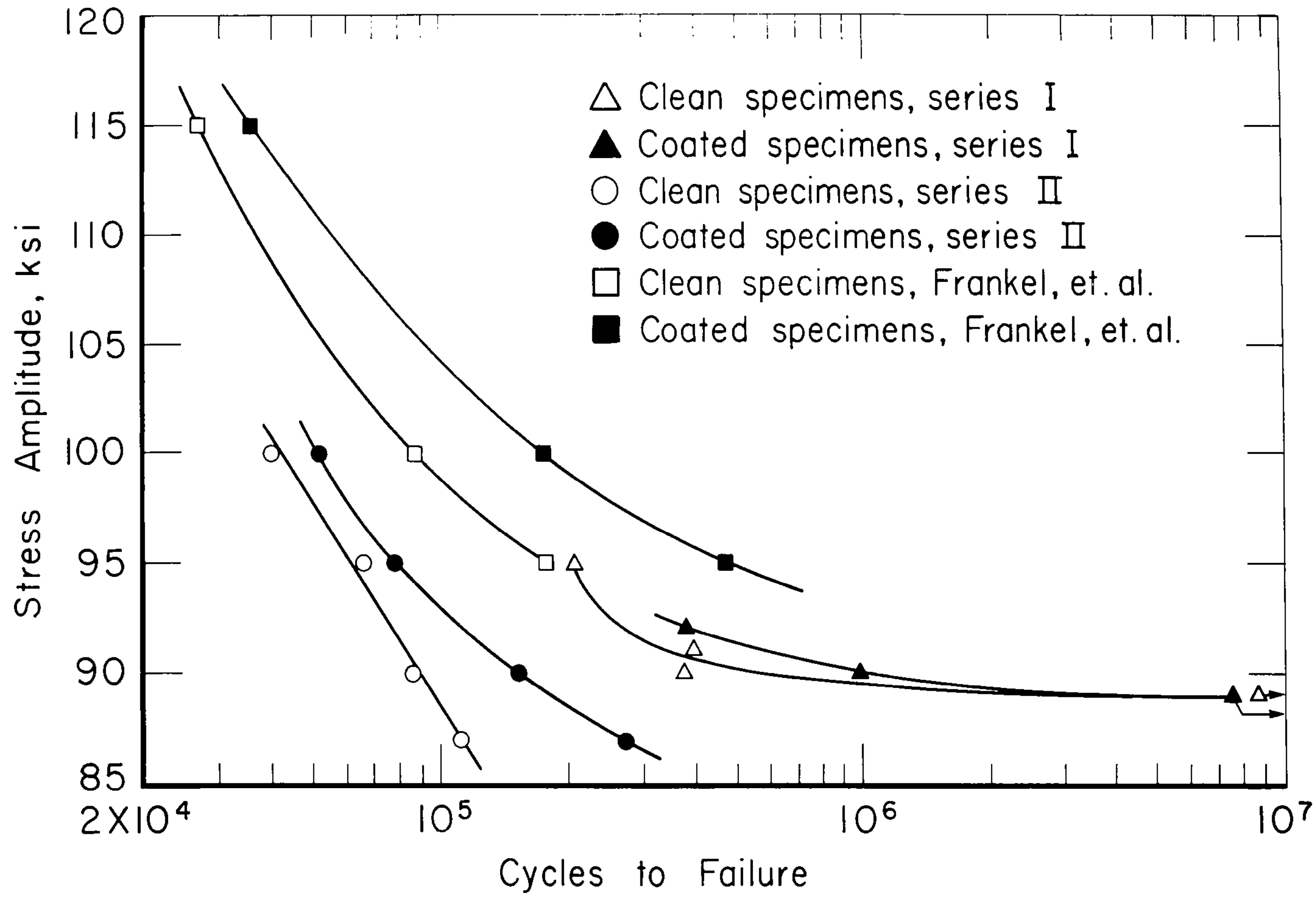

Fig. 4. Effect of dodecyl alcohol on fatigue strength of 4340 steel.

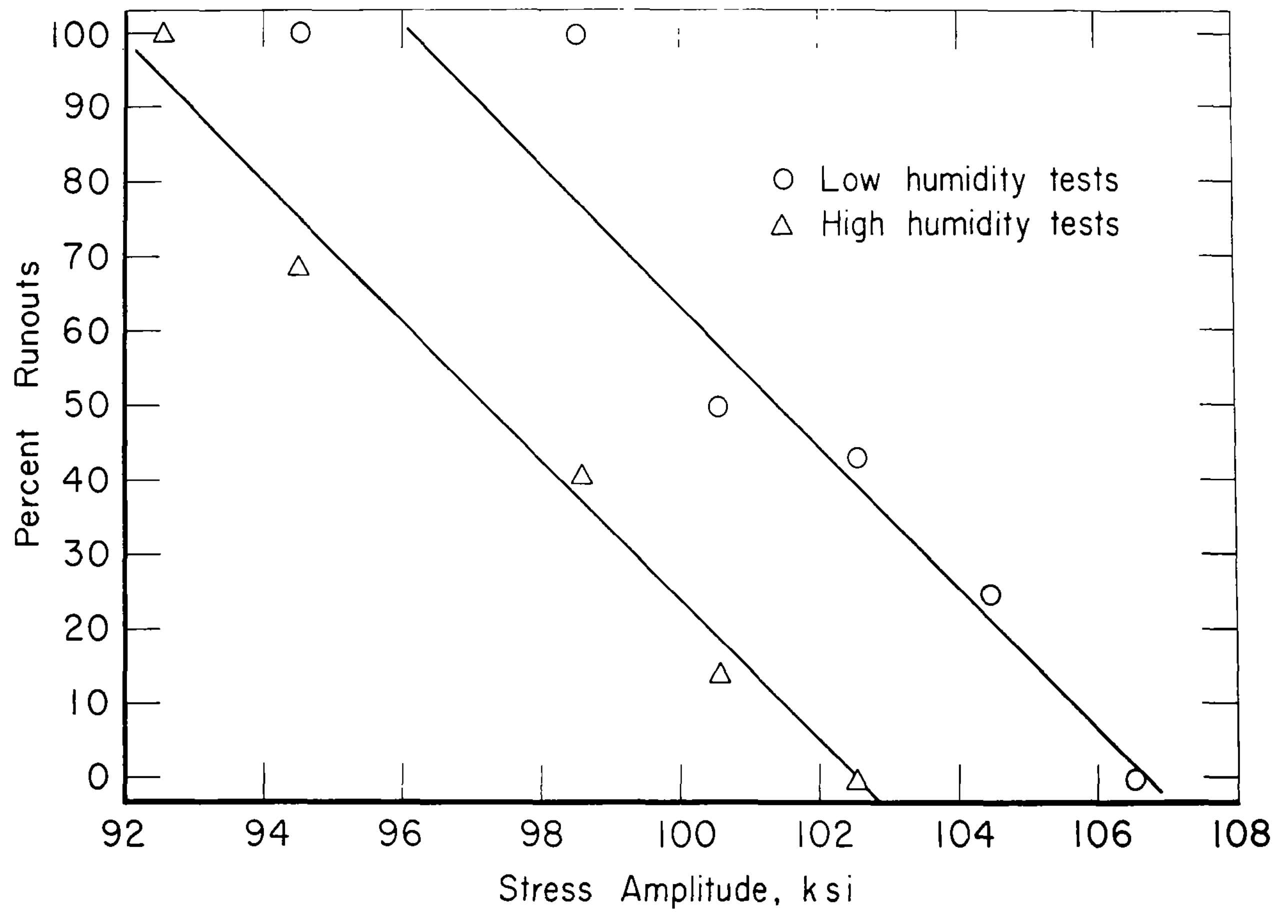

Fig. 5. Effect of humidity on fatigue strength of titanium Ti-4Al-4Mn.

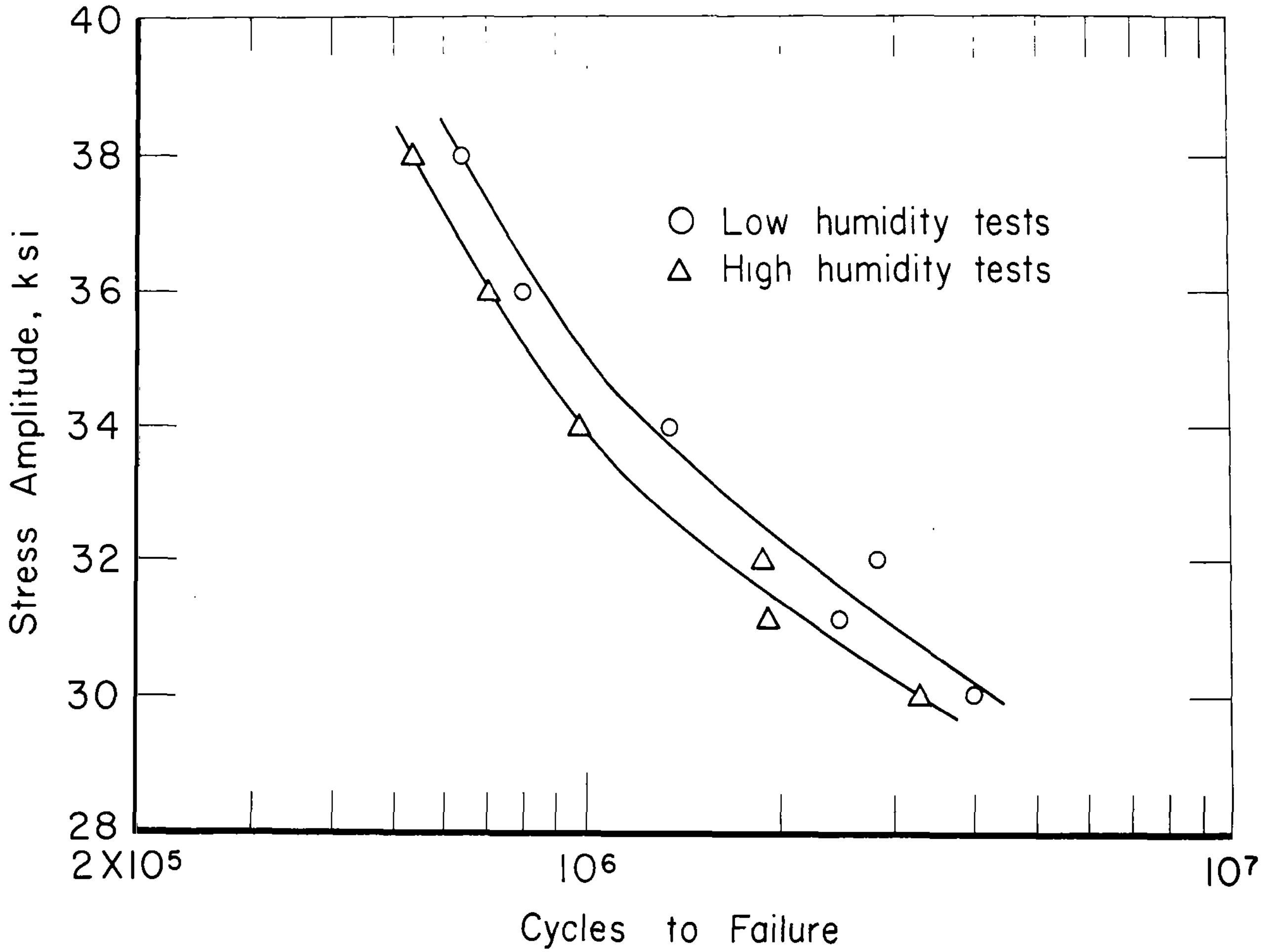

Fig. 6. Effect of humidity on fatigue strength of composition 22 brass.

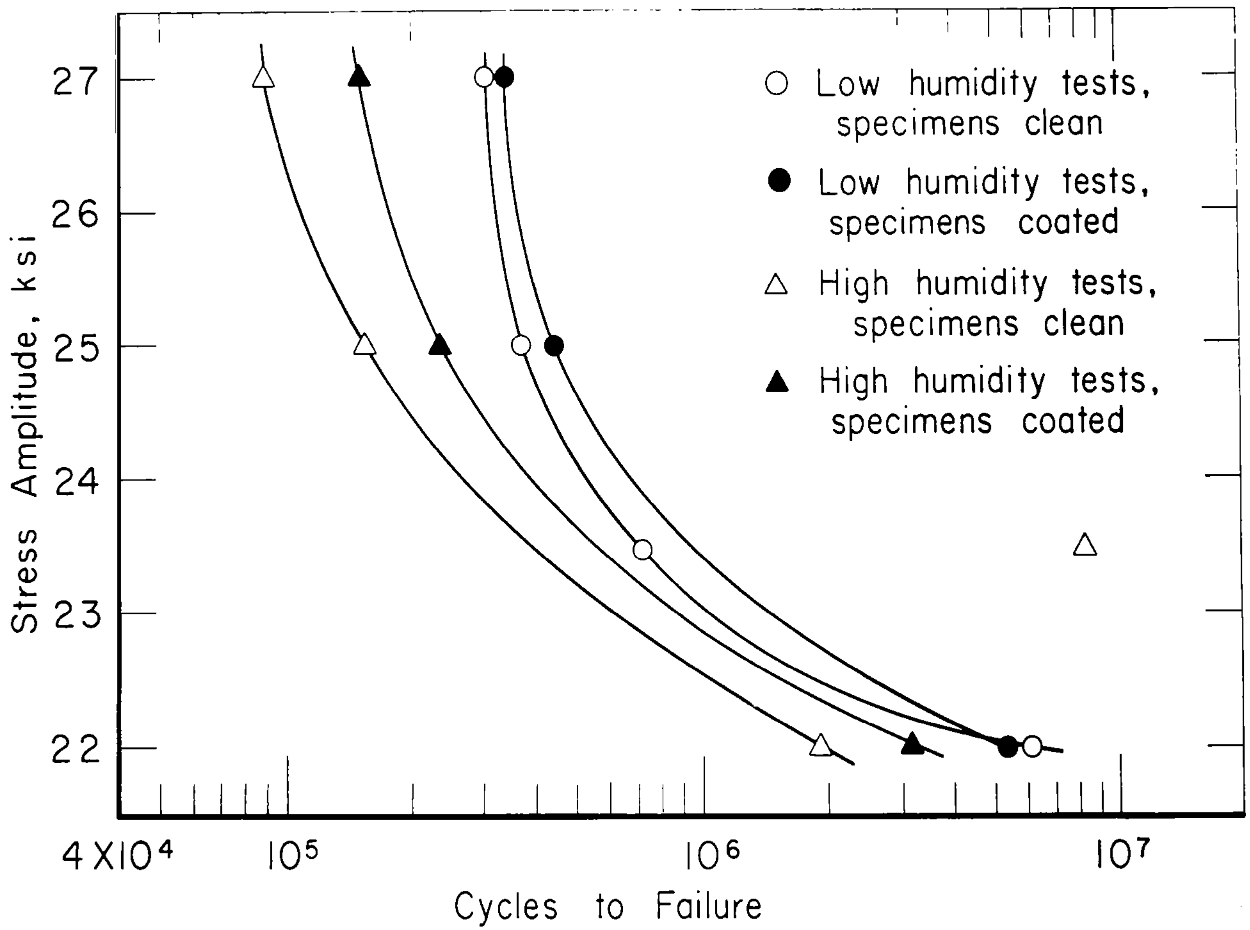

Fig. 7. Fatigue test results for magnesium AZ61A.

Fig. 8. Fracture surfaces of smooth magnesium alloy specimens. Fracture at left occurred in a moist atmosphere, that at the right in a dry one. X 7.

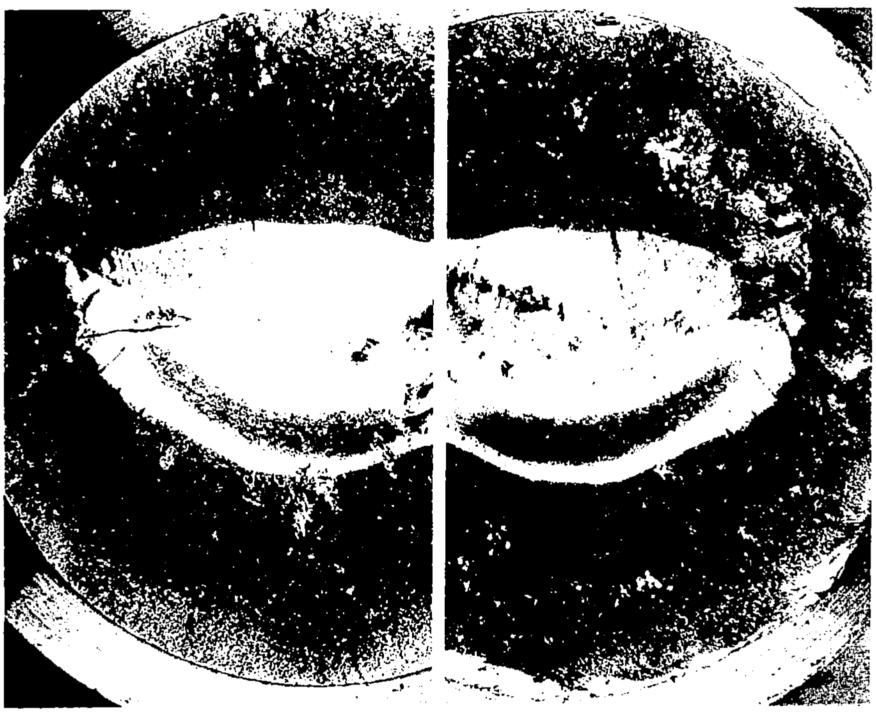

Fig. 9. Two mating halves of fatigue fracture in magnesium AZ61A showing similar tarnish pattern in each half. X 12.

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